

09/15/331

SEGMENTED COMPLEX DIFFRACTION GRATINGS

Related Applications:

h~ The present application is a continuation in part of Application serial number 09/100,592 which was filed June 19, 1998 and which is now ^{CIP} ~~pending~~ ^{abandon}, a continuation in part of Provisional Application 60/070,684, which was filed January 1, 1998, and a continuation in part of Application serial number 08/897,814 filed July 21, 1997 and which is now pending and which is a continuation of Application serial number 08/403,376 which was filed March 13, 1995 and which is now abandoned.

Field of the Invention:

The present invention relates to optical communication systems and more particularly to the use of complex gratings in communication systems.

Background of the invention:

Many present optical communication systems utilize wavelength division multiplexing (WDM) to increase the capacity of optical fibers. Co-pending patent applications SN 08/403,376 and 60/070,684 which are referenced above describe a technology for increasing the capacity of optical systems by utilizing a different type of multiplexing which can be termed optical code division multiple access (hereinafter OCDMA). OCDMA systems encode different communication channels with different temporal codes as contrasted to the coding in WDM systems wherein different channels use different wavelengths of light.

1 Co-pending patent applications SN 08/403,376 and 60/070,684 describe diffraction
2 gratings which consist of multiple sinusoidal subgratings, each subgrating having a
3 specific amplitude and spatial phase. Such gratings can deflect optical pulses from a
4 specific input direction to a specific output direction while simultaneously multiplying the
5 Fourier spectrum of the input pulse by a predetermined filtering function. The output
6 signals are a cross-correlation between the input waveform and the grating encoded
7 temporal waveform. The gratings described in the referenced co-pending applications
8 have a complex profile. They can accept input beams and generate spectrally filtered
9 output beams propagating in one or more output directions. The filtering function of the
10 device is programmed by choice of grating profile. By suitable programming, multiple
11 transfer functions may be realized, each having its own specific input and output
12 direction.

13
14 **Summary of the present invention:**

15 The present invention provides a structure (i.e. a segmented grating) which applies a
16 designated complex-valued spectral filtering function to the input optical field and emits
17 a filtered version of the input field in an output direction and a method for making such a
18 structure. Grating devices, comprised of one or more segmented gratings after the
19 present invention can be used, for example, in OCDMA data links to temporally code
20 optical signals with specific codes such that multiple coded channels can simultaneously
21 be transmitted through the same link and then be decoded into separate channels at the
22 output of the system. The segmented gratings of the present invention can also be
23 utilized in any application area wherein the ability to effect programmable spectral
24 filtering is utilized. The segmented gratings fabricated in accordance with the present
25 invention consist of a series of spatially distinct subgratings arrayed end to end. Each

1 subgrating possesses a periodic array of diffraction structures (lines or more general
2 elements). The overall transfer function of the segmented grating is determined by
3 controlling (a) the spatial periodicity or frequency of each subgrating, (b) the amplitude
4 of each subgrating, (c) the spacing between the last diffraction structure (or line) on each
5 subgrating and the first diffraction structure (or line) of the successive subgrating, and
6 (d) the optical path length and transparency through each subgrating, or each
7 subgrating plus additional material layers utilized to control optical path length and
8 transparency.

9

10 **Brief Description of the Figures:**

11 Figure 1A is an overall diagram of a multiplexing/demultiplexing system utilizing the
12 present invention.

13

14 Figure 1B shows in more detail one of the optical paths shown in Figure 1A.

15

16 Figure 2A shows a top view of a segmented grating fabricated in accordance with the
17 present invention.

18

19 Figure 2B shows a side view of a segmented grating fabricated in accordance with the
20 present invention.

21

22 Figure 3A is a schematic diagram showing the input angle and the output angle at which
23 light is passed through the segmented grating.

24

1 Figure 3B is a schematic diagram showing the angle between the plane containing the
2 input and output beams and the x axis, as measured in the x-y plane.

3

4 Figure 3C shows a temporally coded optical pulse composed of 4 time slices that is
5 incident on a segmented grating of 4 contiguous equal width subgratings.

6

7 Figure 4 shows a first technique for fabricating segmented gratings according to the
8 present invention.

9

10 Figure 5 shows a second technique for fabricating segmented gratings according to the
11 present invention.

12

13 Figure 6 shows a third technique for fabricating segmented gratings according to the
14 present invention.

15

16 Figure 7 shows a side view of two subgratings of a segmented grating with different
17 optical thickness.

18

19 Figure 8 shows a side view of two subgratings of a segmented grating which have a saw
20 tooth blaze.

21

22 Figure 9 shows a four channel OCDMA system.

23

24

25

1 **Detailed Description of a Preferred Embodiment:**

2 Figure 1A is an overall diagram of an OCDMA communication system which utilizes the
3 segmented diffraction grating of the present invention to perform optical multiplexing and
4 demultiplexing. Short-pulse laser 10 generates a coherent beam of light 12. Beam
5 splitter 13 divides the light into two beams 15 and 16. Beams 15 and 16 are each
6 individually modulated by modulators 15a and 16a respectively, thereby generating
7 modulated beams 15b and 16b. The modulation of each of the beams is done in
8 response to an external data stream not explicitly shown in Figure 1. Beams 15b and
9 16b consist, either by virtue of the operative character of the laser source 10, the action
10 of the modulators 15a and 16a, or a combination of the two, of a stream of bits whose
11 temporal character matches the designed input pulses of grating 19.

12
13 Each of the beams 15b and 16b is directed at grating 19 so that it is incident on the
14 grating 19 at an angle that differs for each beam. Grating 19 is a grating device
15 comprised of two superimposed segmented gratings operative on beams 15b and 16b
16 to produce separate output time codes in optical transport 11 for each of the input
17 beams. (The coding technique and the details of grating 19 are described below). The
18 combined coded beam is transported to a second grating 19a via an optical transport
19 device 11 which may for example be an optical fiber. Grating 19a is a grating device
20 also composed of two superimposed segmented gratings operative on the time codes in
21 beam 11 to produce output beams 15c and 16c, respectively. Beams 15c and 16c are
22 modulated identically to the corresponding beam 15a or 16a, respectively. (The
23 decoding technique and the details of grating 19a are described below). The content of
24 beams 15c and 16c is detected by detectors 15d and 16d and it is thus turned back into

1 electrical signals which correspond to the signals that activated modulators 15a and
2 16a.

3

4 It is noted that while the embodiment shown herein combines two beams into one coded
5 beam, three, four, or more beams could similarly be multiplexed into one beam using
6 OCDMA coding. The combined coded beam could be transmitted over a transmission
7 system and then the beams could be demultiplexed into the original signals.

8 Figure 1B shows the optical lenses and spatial filters associated with passing one of the
9 beams through gratings 19 and 19a. As shown in Figure 1B the light beam 16b is

10 passed through a collimating lens 6a so that the light beam illuminates the entire

11 operative width of the two dimensional segmented grating 19sg16 contained within

12 grating device 19. A second lens 6B focuses the light passing through grating device 19

13 into optical transport 11. Spatial filtering provided by means of a dedicated element 8a

14 or consequent to entry into the optical transport selects the operative angular output

15 channel of the segmented grating 19sg16. At the end of optical transport 11 a second

16 collimating lens 7a illuminates segmented grating 19asg16 over (constituent to grating

17 device 19a) over its operative width and the light passing through grating 19a is focused

18 by collimating lens 7b. A spatial filter 8b following lens 7b selects the operative output

19 angular channel of the segmented grating 19asg16 of grating 19a. Figure 1B only

20 shows the elements associated with one data path. The system includes mechanism

21 for collimating each of the beams 15b and 16b, and providing for said beams to

22 illuminate corresponding segmented gratings 19sg15 and 19sg16 within grating 19 at a

23 different angle. A separate lens 6a for each input beam provides an exemplary

24 mechanism. Alternatively, a single lens and control over the launch conditions of the

25 input beams toward the single lens provides equivalent function. Exemplary spatial

1 control comprises a spatial filter in the front focal plane of said single lens with apertures
2 sufficiently small to provide diffractive grating filling. At the output of grating 19a, there
3 is a mechanism for providing a spatial Fourier decomposition of the angular output of
4 the segmented gratings comprising grating 19a and appropriate spatial filtering
5 mechanisms for selecting the multiple operative angular output channels. A single lens
6 provides an exemplary mechanism for providing spatial Fourier decomposition.
7 Apertures placed in the focal plane of said single lens then provides means of selecting
8 operative angular channels. Other means for selecting operative angular channels are
9 are known in the art

10

11 Gratings 19 and 19a through their constituent segmented gratings are designed to
12 accept light from one or more directions and to redirect the light into one or more output
13 directions in a manner that is dependent on the temporal waveform of the input light.
14 Considering a specific input direction and one of the output directions associated with
15 this specific input direction, the grating's functions can be summarized as follows: A
16 portion of each spectral component of the input light field is mapped into the output
17 direction with a controlled amplitude and phase. The grating applies a designated
18 complex valued spectral filtering to the input optical field and emits the filtered version of
19 the input field in the output direction. The spectral resolution of the filtering function is
20 determined by the physical size of the enabling segmented grating constituent to the
21 operative grating device along with the input and output angles of the light beam relative
22 to the grating. The spectral mapping between each input direction and each output
23 direction may be programmed essentially independently through use of dedicated
24 segmented gratings for each mapping. This is explained in the previously referenced
25 co-pending applications, the description of which is incorporated herein by reference.

1 In the present invention, each independently controllable spectral transfer function is
2 controlled by a segmented grating.

3

4 Figure 2A shows one segmented grating fabricated in accordance with the present
5 invention. Grating 19 and 19a contain two such structures superimposed on each other
6 as to form one combined grating. The combined grating thus incorporates the structure
7 of the two individual segmented gratings. We focus now on the design of a single
8 segmented grating. Grating devices incorporating multiple segmented gratings are
9 designed through repetitive application of single segmented grating procedures. The
10 segmented grating has N spatially distinct subgratings or sections 1 to N. In the
11 embodiment shown N is equal to eight. An exemplary cross section of the segmented
12 grating is shown in Figure 2B. Figure 2B is only presented for illustrative purposes to
13 show that the line structure on each of the subgratings comprising the segmented
14 grating has its own amplitude and phase.

15

16 In order to mathematically define the structure of the subgratings contained within one
17 segmented grating, it is first necessary to define a set of coordinates and angles
18 descriptive of the segmented grating and associated optical input and output directions.

19 For convenience, we chose the origin of the reference coordinate axes to lie in the
20 center of the segmented grating. The segmented grating surface is taken to coincide
21 with the x-y plane. We define two lines each of which passes through the coordinate
22 center with the first line parallel to the optical input direction and the second parallel to
23 the optical output direction. We refer to these two lines as the input and output lines,
24 respectively. The input and output lines define a plane, referred to herein as the
25 input/output plane. The mathematics presented herein has the x-axis located in the

1 input/output plane. Other embodiments of the invention could have structures wherein
2 the z-axis is noncoplanar with the input and output lines. Figures 3A and 3B show a
3 schematic diagram of a segmented grating structure showing input angle (θ_{in}) and output
4 angle (θ_{out}) in the input/output plane. The angular separation between the input (output)
5 direction and the z axis is θ_{in} (θ_{out}), where the angles are positive as shown in Figure 3A.
6 Figure 3B shows the angle θ_a between input/output plane and the x axis as measured in
7 the x-y plane. Thus, Figures 3A and 3B show the geometrical arrangement of a
8 segmented grating relative to a particular input and output optical field. For the particular
9 segmented grating under consideration, we define the groove-normal line as the line
10 perpendicular to the grooves lying in the plane of the segmented grating surface and
11 passing through the origin. As described above, the groove-normal line is contained
12 within the input/output plane. Other embodiments of the invention could have a groove-
13 normal line at other locations relative to the input/output plane.

14
15 When the input/output plane contains the z axis, the diffractive structures (grooves) that
16 redirect and spectrally filter the input optical beam into the output direction lie
17 perpendicular to the input/output plane and lie within or on the surface of the segmented
18 grating. We reiterate that multiple segmented gratings having the same or different
19 values of θ_a can be colocated on the same substrate with any degree of overlap.

20 Grating devices may require a single segmented grating structure, multiple spatially
21 superimposed segmented grating structures, or a combination of spatially superimposed
22 and spatially separated segmented grating structures fabricated onto a single substrate.

23 Grating 19 in Figure 1A is comprised of two segmented grating structures.

24

1 Grating 19 utilizes transmissive segmented gratings, but all particulars discussed herein
 2 can be transferred as known in the art to a reflective grating geometry. Each input
 3 optical beam illuminates the active width of each segmented grating structure with which
 4 it is intended to interact. It is noted that grating 19 and the segmented gratings that it
 5 supports are essentially planar and arranged parallel to the x-y coordinate plane. As in
 6 the case of simple monospaced diffraction gratings, segmented gratings may be
 7 implemented with nonplanar surface geometry. For example a segmented grating could
 8 be supported by a nonplanar (e. g. concave) substrate. The use of non-planar surface
 9 geometry allows for the control over the spatial wavefront of input optical beams in
 10 addition to the spectral content control that is afforded by grating segmentation.

11
 12 A single segmented grating structure is fabricated in the form of a series of N spatially
 13 distinct subgratings arrayed side to side whose collective span defines the operative
 14 width of the segmented grating. Each subgrating possesses a periodic array of
 15 diffractive structures (grooves) arranged in a plane perpendicular to the input/output
 16 plane. The spacing between diffractive structures within the N successive spatial
 17 subgratings is typically but not necessarily the same. The N subgratings are written or
 18 otherwise created on the grating such that each occupies a specific subsection of the
 19 overall grating surface and subgratings appear successively as one passes along the
 20 groove-normal line. All subgrating constituents of a particular segmented grating
 21 typically but not necessarily have the same span perpendicular to the groove-normal
 22 line, i.e. height. The spatial interval between the last diffractive structure (groove) of
 23 each subgrating and the first diffractive structure (groove) of the successive subgrating
 24 is controlled as will be described.

25

1 Control over groove positioning provides control over relative spatial phase of adjacent
2 subgratings. Also controlled is the amplitude of the diffractive structures within a given
3 subgrating. The manner in which subgrating spacing and amplitude is controlled
4 determines the spectral transfer function of the grating. The optical thickness of the
5 various subgratings comprising a segmented grating structure can be controlled by
6 variation of substrate thickness, addition of phase masks, or other means known in the
7 art to provide additional control over the spectral transfer function of the grating.
8 Variation of optical thickness under a spatial subgrating or the separation between
9 subgratings both act to control the relative phase of light transferred from the input to
10 the output directions. Active devices can be added between the subgratings to
11 dynamically change subgrating-subgrating separation to allow for the dynamical
12 reprogramming of the spectral filtering function. Active devices to control the optical
13 thickness of subgratings inclusive of overlays can be added to provide an alternative
14 means of dynamical reprogramming of the spectral filtering function.
15
16 The representative segmented grating shown in Figure 2 has eight spatial subgratings.
17 The spatial subgratings have essentially equal extent along the groove normal line;
18 however, spatial subgratings of dissimilar extent can be employed. The representative
19 segmented grating is a transmissive phase grating, but it could be a reflective,
20 amplitude, or other generalized physical grating type.

21
22 We represent the transmissive optical phase shift versus position of one
23 constituent subgrating, labeled by the subscript i , of a segmented grating device by the
24 following mathematical expression

$$h_i(x') = A_i f_i(2\pi(x' - x_i) / \Lambda_i) + \varphi_i \quad \{\text{for } x_i^a \leq x' \leq x_i^b\} \quad (1)$$

where x' represents the spatial position coordinate along the groove-normal line, x_i is the spatial position shift of the i^{th} subgrating groove pattern, the function f_i represents a particular groove profile and is periodic in its argument on the scale of 2π and modulates between the values of 0 and 1, φ_i is an optical phase shift introduced by a variation in substrate thickness or superimposed phase mask, A_i is a real-valued amplitude factor, x_i^a and x_i^b are the edge positions of subgrating i , and Λ_i is the spatial period of the i^{th} subgrating. Outside the prescribed spatial interval, $h_i(x')=0$. The subscript i ranges from 1 to N and denotes individual spatial subgratings. By specifying the parameters A_i , φ_i , x_i , and Λ_i for the subgratings employed, a wide range of spectral filtering functions can be encoded.

The parameters A_i , φ_i , x_i , and Λ_i necessary to produce specific spectral transfer functions can be chosen in a variety of ways. Assume that a grating is to be constructed that provides a particular spectral transfer function $T(\nu)$ (where ν is the optical frequency) as approximated by N transmission coefficients each of which corresponds to one of N contiguous frequency channels collectively spanning the full non-zero width of $T(\nu)$. To accomplish this, the segmented grating will require approximately N subgratings. We assume that $T(\nu)$ is nonzero over a specific spectral region of width $\delta\nu$ centered about the frequency ν_0 . To provide filtering with the specified resolution, the subgratings will require a spatial width given approximately by $c/[\delta\nu(\sin\theta_{\text{in}}+\sin\theta_{\text{out}})]$ where c is the speed of light. The total width of the grating will thus be approximately given by $Nc/[\delta\nu(\sin\theta_{\text{in}}+\sin\theta_{\text{out}})]$ assuming that the subgratings are laid down contiguously.

1

2 For example, if $\delta\nu=100$ GHz, $\theta_{in}=0^\circ$, $\theta_{out}=45^\circ$, and $N=8$ the complete spatial width of a
3 segmented grating capable of representing $T(\nu)$ will be approximately 3.4 cm.

4

5 The parameters (A_i , φ_i , x_i , and Λ_i) for all of the N subgratings comprising the
6 segmented grating determine its spectral transfer function. Given the subgrating
7 parameters, the spectral transfer function of the segmented grating can be determined.
8 Conversely, given a specific spectral transfer function the subgrating parameters which
9 must be employed to create a segmented grating with that transfer function can be
10 determined. It should be understood that while the mathematics presented herein
11 contain certain constraining assumptions in order to facilitate an explanation of the
12 preferred embodiment of the invention, the equations could be generalized without
13 departing from the invention.

14

15 We first give an expression for the spectral transfer function exhibited by a segmented
16 grating in terms of subgrating parameters. Under the assumptions that 1) $A_i \ll 1$ or
17 $A_i = A = \text{constant}$, 2) plus or minus first order ($m = \pm 1$) grating output is employed, and 3)
18 the N subgratings have equal spatial width ($d = x_i^b - x_i^a = \text{constant}$), equal spatial period
19 ($\Lambda_i = \Lambda = \text{constant}$), and are laid down contiguously, the spectral transfer function of the
20 segmented grating may be written as a sum over subgrating parameters as follows:

$$21 \quad T(\nu) = F(\nu) \sum_{i=1}^N a_i \exp(j\Phi_i) \quad (2a)$$

22 where:

$$23 \quad a_i = A_i \exp(j(\varphi_i - 2\pi x_i m / \Lambda)), \quad (2b)$$

$$\Phi_i = \pi(x_i^a + x_i^b)(\beta v - m / \Lambda), \quad (2c)$$

and

$$\beta = (\sin \theta_{in} + \sin \theta_{out}) / c. \quad (2d)$$

Here, $F(v)$ is the spatial Fourier transform of a subgrating given by

$$F(v) = \frac{jC}{N} \text{sinc}(\pi d(v\beta - m / \Lambda)), \quad (2e)$$

where j is $\sqrt{-1}$, and C is a constant dependent on the groove profile and contains a phase factor dependent on the choice of x' -origin. The function $\text{sinc}(x)$ is defined as equal to $\sin(x)/x$. In writing Eq. (2), it is assumed that the output signal is derived from the plus ($m=1$) or minus one ($m=-1$) diffractive order of the subgratings. Analogous expressions for higher and negative orders follow as per known in the art.

If one wishes to design a segmented grating having a specific transfer function, it is necessary to determine appropriate parameters for each subgrating. To do this one first solves Eq. (2a) for a_i and obtains

$$a_i = \beta d \int_{m/(\beta\Lambda) - 1/(2\beta d)}^{m/(\beta\Lambda) + 1/(2\beta d)} \frac{T(v)}{F(v)} \exp(-j\pi(v\beta - m / \Lambda)(x_i^a + x_i^b)) dv \quad (3)$$

From Eq. (2b) one finds that A_i is equal to the amplitude of a_i . The quantities x_i and ϕ_i both determine the phase of a_i as seen in the equations above. An appropriate combination of x_i and ϕ_i consistent with Eq. (2b) and Eq. (3) can be chosen at the convenience of the grating designer. The parameter Λ is chosen so the light of carrier

1 frequency ν_o is maximally diffracted from θ_{in} to θ_{out} using the well-known grating equation
 2 $\sin(\theta_{in}) + \sin(\theta_{out}) = m\lambda_o / \Lambda$ where $\lambda_o = c/\nu_o$ is the center wavelength of the desired transfer
 3 function. The angles θ_{in} and θ_{out} are designer inputs as is $T(\nu)$. Mathematically
 4 speaking, Λ is chosen as the solution of the mathematical equation $\beta\nu_o\Lambda = m$.

5
 6 Alternatively, a more general solution for obtaining the subgrating parameters is to
 7 calculate the continuous grating profile that will generate the desired continuous transfer
 8 function. If the transmissive phase of a grating as a function of x' is given by

$$9 \quad h(x') = -j \ln \left[\sqrt{2\pi\beta D} \int_{-\infty}^{+\infty} T(\nu) \exp(-j2\pi\beta\nu x') d\nu \right], \quad (4)$$

10 the spectral transfer function of the grating in direction θ_{out} will be $T(\nu)$, where D is the
 11 width of the grating. Again θ_{in} , θ_{out} , and $T(\nu)$ are designer inputs. It is necessary to
 12 convert the continuous transmissive phase profile given by Eq. (4) to a segmented
 13 phase profile consistent with subgrating fabrication. Parameters descriptive of constant
 14 phase segments which can be directly mapped onto the parameters defining constituent
 15 subgratings can be determined as follows: The continuous surface phase profile, $h(x')$,
 16 will generally consist of a carrier spatial modulation with a slowly varying amplitude and
 17 phase shift. A representative average of the spatial phase shift over the physical extent
 18 of subgrating i is determined and the values of ϕ_i and x_i are adjusted in a convenient
 19 combination to match the determined spatial phase shift determined from Eq. (4).
 20 Similarly, a representative value of the grating amplitude from Eq. (4) within the physical
 21 extent of subgrating i is determined and A_i is set equal to this grating amplitude. The
 22 spatial period Λ_i is set equal to the carrier modulation period of $h(x')$ as given by Eq. (4).
 23 A variation to the approach just given is to determine a spatial carrier, amplitude, and

1 phase within the extent of each subgrating separately. This procedure allows for the
2 variation of Λ_i from subgrating to subgrating.

3

4 For a segmented grating to perform the function of optical cross-correlation between
5 optical input waveforms and a reference optical waveform, the grating's spectral transfer
6 function should be the complex conjugate of the spectrum of the reference optical
7 waveform. The function of optical cross correlation here means that the electric field
8 emitted by the grating in the operative output direction represents the temporal cross
9 correlation between a) an input optical waveform incident on the grating along the
10 operative input direction and b) the specific reference optical waveform whose
11 conjugated spectrum coincides with the grating's spectral transfer function.

12

13 Consider a reference optical waveform whose time profile is represented as a sequence
14 of N contiguous time slices within which the amplitude and phase of the optical field is
15 constant. In time slice i ($i=1, \dots, M$), the electric field has constant amplitude B_i and phase
16 ϕ_i . The reference waveform is thus determined by the set of complex numbers
17 $[B_1 \exp(j\phi_1), B_2 \exp(j\phi_2), \dots, B_M \exp(j\phi_M)]$ along with the optical carrier frequency in each time
18 slice and the overall temporal duration of the waveform. Figure 3C schematically
19 illustrates an input optical waveform of the form $[C_1 \exp(j\phi'_1), C_2 \exp(j\phi'_2), \dots, C_4 \exp(j\phi'_4)]$
20 incident on a segmented grating.

21

22 When an optical waveform is incident on the grating, the grating will spectrally filter the
23 incident waveform as described by the grating spectral transfer function for the particular
24 θ_{in} and θ_{out} employed. If the grating is to perform the function of cross-correlation
25 against the reference optical waveform, the subgratings should have parameters that

1 are the "time-reversed" complex conjugate of the reference optical waveform, e.g. $[a_1,$
2 $a_2, \dots, a_8] = [B_8 \exp(-j\phi_8), B_7 \exp(-j\phi_7), \dots, B_1 \exp(-j\phi_1)]$ where the subgrating parameters are
3 related to a_i by equation (2b) given the assumptions in deriving Eqs. (2a-3) are met.
4 The operation of cross-correlation may be used to multiplex and demultiplex optical
5 signals.

6
7 It is noted that the groove profile affects primarily the diffraction efficiency of the grating.
8 This affects the magnitude of the spectral transfer function or the constant C in Eq. (2e).

9
10 The following specifies the gratings employed in an exemplary two-channel
11 multiplex/demultiplex system as in Figure 1a. Grating devices 19 and 19a used are
12 each composed of two superimposed segmented gratings. Grating 19 accepts uncoded
13 data streams and launches time-coded data into a common channel. Grating 19a
14 accepts time-coded data and launches distinct time codes into distinct output directions
15 while simultaneously stripping off time-coding. Grating 19a functions through the
16 process of cross-correlation.

17
18 In the present embodiment, gratings 19 and 19a consist of two superimposed
19 segmented gratings. The net transmissive optical phase shift versus position of the
20 gratings is consequently the sum of the transmissive optical phase shift functions for the
21 two constituent segmented gratings.

22
23 In the multiplexer/demultiplexer embodiment presently considered we use a lamellar
24 (square-wave) groove profile with a fifty percent duty cycle. We assume uniform
25 subgrating amplitudes of $A_i = \pi/2$ for the first and second segmented gratings, the

1 diffraction efficiency of grating 19 and grating 19a is approximately 20% in the operative
 2 output directions. If a transmission grating is to be etched into a substrate with optical
 3 index $n_0=1.50$, the etch depth that corresponds to $A_i=\pi/2$ phase modulation is given by
 4 $0.77\mu\text{m}$ for a carrier wavelength of $1.54\mu\text{m}$. The input-output plane contains the z-axis
 5 in this embodiment. The gratings 19 and 19a have eight subgratings, each subgrating
 6 has a width of 1mm , thus the total grating width is 8mm . The segmented gratings
 7 comprising grating 19 and 19a have $\theta_a=0^\circ$ and are designed for optical data streams
 8 having the carrier frequency 195 THz (a carrier wavelength $\lambda=1.54\mu\text{m}$).

9
 10 The optical data channels controlled by a first segmented grating constituent of grating
 11 19 are specified to have the input and output angles $\theta_{in}=17.94^\circ$ and $\theta_{out}=0^\circ$. The grating
 12 spacing is $\Lambda=5\mu\text{m}$ for all subgratings of the first segmented grating. The first
 13 segmented grating is designed to accept temporally short input pulses of optimal
 14 duration $\Delta\tau_p=1\text{ ps}$ along $\theta_{in}=17.94^\circ$ and generate temporally coded pulses along the
 15 multiplexed output direction $\theta_{out}=0^\circ$. To produce output pulses of approximate duration
 16 $\tau_p=8\text{ ps}$ with the following temporal code

$$[1, 1, 1, \exp(j2\pi/3), \exp(j4\pi/3), 1, \exp(j4\pi/3), \exp(j4\pi/3)]$$

18 the corresponding subgrating x_i and φ_i parameters for the first segmented grating are

$$[x_1, x_2, \dots, x_8]=[0.0\mu\text{m}, 0.0\mu\text{m}, 0.0\mu\text{m}, -1.67\mu\text{m}, 1.67\mu\text{m}, 0.0\mu\text{m}, 1.67\mu\text{m}, 1.67\mu\text{m}]$$

20 and

$$[\varphi_1, \varphi_2, \dots, \varphi_8]=[0, 0, 0, 0, 0, 0, 0, 0].$$

22 The second segmented grating consists of a set of eight subgratings with the following
 23 common specifications: $\Lambda=3\mu\text{m}$, $\theta_{in}=30.89^\circ$, $\theta_a=0^\circ$, and $\theta_{out}=0^\circ$. The second segmented
 24 grating, like the first, accepts temporally brief data bits of optimal duration $\Delta\tau_p\approx 1.71\text{ ps}$

1 moving along its input direction and generates temporally coded bits of approximate
2 duration $\tau_p=13.7$ ps into its output direction. Segmented gratings one and two have a
3 common output direction. If the coded output bits from segmented grating two are to
4 have the following form

$$5 \quad [1, \exp(j2\pi/3), \exp(j4\pi/3), 1, \exp(j2\pi/3), \exp(j4\pi/3), 1, \exp(j2\pi/3)],$$

6 the corresponding subgrating parameters of the second segmented grating are

$$7 \quad [x_1, x_2, \dots, x_8]=[0.0\mu\text{m}, -1.0\mu\text{m}, 1.0\mu\text{m}, 0.0\mu\text{m}, -1.0\mu\text{m}, 1.0\mu\text{m}, 0.0\mu\text{m}, -1.0\mu\text{m}]$$

8 and

$$9 \quad [\varphi_1, \varphi_2, \dots, \varphi_8]=[0,0,0,0,0,0,0,0].$$

10 The filtering bandwidth of the second segmented grating is $\delta\nu\cong 1/\Delta\tau_p$ or 0.6 THz.

11
12 The multiplexed beams copropagating in optical transport 11 may be demultiplexed at
13 grating 19a. The demultiplexing grating 19a in Figure 1A and 1B is identical in design to
14 grating 19. For an input angle into grating 19a of $\theta_{in}=0^\circ$ the demultiplexed output beams
15 are collected in angles $\theta_{out}=-17.94^\circ$ and $\theta_{out}=-30.89^\circ$ for the first and second reference
16 optical waveforms respectively.

17
18 Given the above grating specifications the laser source 10 as shown in figure 1A must
19 have a maximum temporal pulse width (FWHM) of 1 ps (given by the minimum $\Delta\tau_p$ of the
20 two segmented gratings).

21
22
23 Manufacturing segmented gratings: Using lithography (optical or electron beam)
24 surface profiles can be written onto a substrate point by point. Thus segmented gratings
25 with spatial phase shifts between the subgratings can be written directly onto a

1 transmitting or reflecting surface. Control of subgrating amplitude is also possible using
2 this technique.

3

4 It is also possible to use a variety of holographic techniques to successively or
5 simultaneously record subgratings with controlled surface profile properties.

6

7 Figure 4 illustrates how the segmented grating can be manufactured by spatial
8 repositioning of the grating substrate to produce subgratings with controlled spatial
9 phase. The angle between the two beams or the wavelength of the two beams used in
10 standard holographic recording can be used to control the grating spacing Λ_i . Spatial
11 phase shifts may be introduced between exposures by translating the grating substrate.
12 Thus, the N subgratings can be recorded, as shown in Figure 4, by spatially translating
13 an aperture mask of width $d=D/N$ (where D is the total grating length) by its width N
14 times and exposing the recording material at each mask position. Between exposures,
15 the grating substrate is shifted along the groove-normal line. The substrate shifts a
16 distance x_i relative to a fixed reference prior to exposure of subgrating i. Control of
17 writing beam intensity between subgrating exposures allows for subgrating amplitude A_i
18 control.

19

20 A similar method of producing segmented gratings comprised of subgratings with spatial
21 phase shifts uses single exposure holography with a phase-code mask having the
22 appropriate subgrating phase shifts encoded in its optical thickness. The mask is placed
23 in one of the two interfering beams in close proximity to the substrate. If these beams
24 are incident from opposite sides of the substrate, this phase-mask can be contacted
25 directly onto the grating substrate.

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Figure 5 shows a holographic method for fabricating gratings with N subgratings with controlled spatial phase shifts. This technique controls the phase-difference, ϕ_i , between the two optical writing beams as shown in Figure 5. Control of writing beam intensity allows for control of subgrating amplitude as well. The optical phase-difference determines the position of the interference pattern on the sample where the beams overlap, and their intensity controls the modulation amplitude of the interference pattern. The subgratings are recorded by illuminating the whole sample region with the interference pattern, but using an aperture of width d so that only the region behind the aperture is exposed and recorded. By spatially shifting the aperture across the sample in N steps it is possible to write a series of N subgratings, with each grating having a phase determined by the phase-difference ϕ_i used during exposure of the i^{th} subgrating.

Figure 6 illustrates an approach to producing subgratings termed the "master phase mask" approach. In this approach a single writing beam is used in conjunction with a master phase mask diffraction grating. A single beam incident on a master grating will be diffracted to yield one or more extra output beams. The incident and diffracted beams will interfere producing an interference pattern that can be used to record a near duplicate of the master grating as known in the art. This property of diffraction gratings makes it possible to use a master grating to generate the interference pattern needed for the grating. The phase in each subgrating is imparted by translating the master grating or the recording substrate between successive masked subgrating exposures.

1 Control of substrate optical thickness and thus phase shift φ_i : Figure 7 shows a two
 2 segment grating wherein the subgratings are written onto a substrate of varying
 3 thickness. Variation in substrate thickness provides for control over the subgrating
 4 parameter φ_i . More generally, φ_i can be controlled by any of the means known in the
 5 art for varying the optical path length of the subgrating substrates. For example, index
 6 of refraction changes between subgrating substrates provides for control over φ_i .

7
 8 A variety of fabrication methods support control over φ_i . Lithography provides for
 9 changes in surface level (and hence substrate thickness) as well as groove profile.
 10 Programmed lithographic variations in surface level thus provide control over φ_i .
 11 Holographic, lithographic, or mechanical ruling methods can be implemented on a
 12 substrate that has been prepared to have specified optical thickness throughout the
 13 spatial region occupied by each subgrating. Control over optical thickness can be
 14 achieved by any of the means known in the art including but not limited to etching and
 15 thin-film coating.

16
 17 The value of φ_i for each subgrating can also be controlled through use of a separate
 18 phase mask placed over a constant thickness substrate.

19
 20 Production of Segmented gratings through Fourier Synthesis: A grating may be
 21 made by a Fourier synthesis method by superposition of multiple periodic gratings each
 22 of which spans the entire width of the segmented grating. The constituent periodic
 23 gratings have relative phases, amplitudes, and spatial periods such that when summed
 24 they result in the segmented grating profile of interest. The constituent periodic gratings

1 are the Fourier components of the desired grating profile. The more Fourier
 2 components used the more sharply defined the subgratings will be.
 3
 4 The gratings can be manufactured by holographic or lithographic methods. By exposing
 5 a photosensitive substrate with multiple holographic exposures each of which writes a
 6 particular constituent periodic grating, the desired grating profile can be recorded.
 7 Lithographic means also provide for multipass writing wherein each pass is employed to
 8 write one constituent periodic grating.

9
 10 Gratings with specific groove profiles (Blazing): By using lithographic and holographic
 11 methods the gratings may have an arbitrary modulation profile which include saw-tooth
 12 blazed, square wave, sine wave, etc. in order to engineer the distribution of power into
 13 the diffraction orders. Figure 8 is a schematic of a grating similar to that shown in
 14 Figure 2B, but with a saw-tooth modulation profile.

15
 16 It is noted that the descriptions of the segmented gratings presented in this document
 17 can be generalized to include gain gratings as well as absorption gratings, fiber gratings,
 18 and gratings in frequency selective materials.

19
 20 Dynamic Gratings: In the embodiments described above, the gratings have been static.
 21 The following describes an embodiment wherein the gratings can be dynamically
 22 reprogrammed with respect to their spectral filtering functions.

23
 24 In the previously described embodiments, the spectral transfer function of the gratings
 25 is determined by the parameters A_i , ϕ_i , λ_i , and Λ_i of its constituent subgratings.

1 Generally speaking, any means known in the art that provides for dynamic control of
 2 one or more of these parameters will enable dynamic reprogramming of gratings. A
 3 variety of construction methods allow for dynamic reconfiguration of gratings. For
 4 example: Control of ϕ_i and A_i through control of substrate or overlay index of refraction.
 5 A grating created by the means described above may be overlain with a material whose
 6 index of refraction can be controlled by any of the standard means known in the art
 7 including, for example, applied electric field, pressure, current, or optical irradiation. If
 8 the means of controlling the index of the overlayer is applied to act differentially over
 9 spatial regions essentially coinciding with the subgratings comprising the grating either
 10 ϕ_i or A_i can be controlled. To control ϕ_i alone, an overlayer may be applied to the side of
 11 the substrate opposite to the grooves. Variation in optical thickness in the overlayer
 12 induced by any means known in the art then allows one to vary ϕ_i . If the overlayer is
 13 applied to the groove side of the grating (filling in the grooves) both ϕ_i and A_i can be
 14 controlled. A_i may be controlled by changing the difference in refractive index between
 15 the grooves and the overlayer. ϕ_i can be controlled by controlling the optical path length
 16 of the overlayer (as in the case when the overlayer is applied on the substrate side
 17 opposite the grooves). The ratio $\Delta A_i / \Delta \phi_i$ may be varied by adjusting the thickness of
 18 the overlayer. Here ΔA_i ($\Delta \phi_i$) is the change in A_i (ϕ_i) introduced by a given change in
 19 refractive index of the overlayer. Control of A_i alone can be achieved by a variety of
 20 means including the addition of overlayers on both sides of the grating substrate and
 21 configuration of the overlayers so that the optical path difference introduced by index
 22 changes of the two layers cancels and thus so does the change in ϕ_i . On the other
 23 hand, the change in amplitude of the phase subgratings is sensitive to the index change

1 of only one of the overlayers and does not cancel. Pure A_i control can also be obtained
2 by stacking two differentially controlled overlayers on the groove side of the grating.
3 Again, the optical path difference on passing through both layers is constrained to be
4 constant.

5

6 Control of the complex φ_i through control of substrate or overlay transmission:

7 In the following paragraph we reinterpret $h_i(x')$ in Eq. (1) to define the generalized
8 complex amplitude transmission function of a grating to be given by:

9
$$H_i(x') = \exp(jh_i(x')) \quad (5)$$

10 In this representation we allow $h_i(x')$ to be complex in order to include gain or absorption
11 gratings in the above presented treatment. When the amplitude factor A_i is considered to
12 be complex, the imaginary part subsequently describes the loss or gain grating
13 amplitude. Furthermore, by generalizing φ_i to be a complex number, we include the
14 possibility of subgrating absorption or gain introduced by a variation in substrate
15 transmission or a superimposed amplitude mask.

16

17 A grating, as described earlier, may be overlain with a material whose optical intensity
18 transmission can be controlled by any of the standard means known in the art including,
19 for example, with a liquid crystal amplitude modulator or an electro-absorptive material.
20 If the means of controlling the transmission of the overlayer is applied to act differentially
21 over spatial regions essentially coinciding with the subgratings comprising the
22 segmented grating, the imaginary part of φ_i can be controlled. Changing φ_i will effect a
23 change in the transfer function $T(v)$ as described in Eqs. (1-4).

24

1 In the preferred embodiment shown in Figure 1, two optical channels are multiplexed
2 using OCDMA coding. As illustrated in the embodiment shown in Figure 9, additional
3 channels can be encoded, multiplexed, transmitted and then demultiplexed. In the
4 embodiment shown in Figure 9, four channels 901, 902, 903 and 904 are modulated by
5 modulators 901a to 904a, multiplexed by grating 919, transmitted on fiber 911,
6 demultiplexed by grating 919a, and then detected by detectors 901d to 904d. The
7 gratings 919 and 919a consist of four superimposed segmented gratings of the type
8 previously described.

9

10 While the invention has been described with respect to preferred embodiments thereof,
11 it will be understood by those skilled in the art that various changes in format and detail
12 may be made without departing from the spirit and scope of the invention. Applicant's
13 invention is limited only by the appended claims.

14